

MEASUREMENTS AND THEORETICAL ANALYSIS OF A FULL SCALE NEMP

TYPE LIGHTNING SIMULATOR FOR AEROSPACE VEHICLES

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In an earlier paper, it was suggested that peaking capacitors such as are used in nuclear electromagnetic pulse simulators be used to supply the fast current rise times which have been indicated in recent researches in the field of lightning spherics and lightning strikes to aircraft. A more quantitative experimental and analytical study has been undertaken to examine the feasibility and the significant parameters for such a system. The results of the studies have indicated that average lightning currents of 20,000 to 40,000 amperes, with moderately fast rise times of 100 nanoseconds (which is an order of magnitude improvement), can be achieved fairly economically, but that rise times of the order of 30 to 50 nanoseconds would increase the cost and design difficulties significantly. What remains to be determined is the statistical distribution of currents and risetimes in strikes to aircraft. A number of flight research programs are currently underway which are accumulating data for establishment of new rise time test standards.

THE RECENT WORK done in the characterization of lightning by the Flight Dynamics Laboratory and NASA has revealed that the risetimes of lightning return stroke components are on the order of 100 nanoseconds. This is an order of magnitude faster than the previously accepted risetime of one microsecond. The faster risetime produces more energy at frequencies of aircraft resonances than previously anticipated. Energy coupling to the aircraft interior can be due to both electric and magnetic field penetration of apertures and the faster risetimes increase this coupling. At present, most impulse generators for lightning simulation are designed to generate one to two microsecond risetimes and cannot simulate the newly-revealed threat. Modifying present generators to

achieve the fast risetimes and large voltage levels is not a simple task because inherent generator resistances and inductances limit the magnitude and risetime of generator output.

ANALYSIS

It is therefore desirable to design a new type of simulator suitable for testing aircraft to this new threat. Design of such a simulator involves both analysis and test. The objective of the analysis phase as discussed in this section is to provide analytic (numerical) results to support the design of such a simulator.

The analytic results fall into three areas:

- o QUANTIFICATION of the results for a test cylinder
- o QUANTIFICATION of results for an F-16 in a proposed simulator
- o INVESTIGATION of pulse generator-shielding requirements.

A test cylinder 30' long and 6' in diameter is used as both an experimental and numerical test bed for investigating the basic simulator concepts. Parameter studies of the cylinder response are accomplished for variations in geometry, pulser waveshaping elements, termination impedances, and spark gap configurations.

These cylinder results are then used to provide insight into the response of a full size aircraft (the F-16) in the proposed full scale simulator design. Parameter studies are also done in this case for variations similar to that in the cylinder case. It was found that the values of injected current and its derivative were greatly dependent upon the size of the peaking capacitor which was used. The size of this

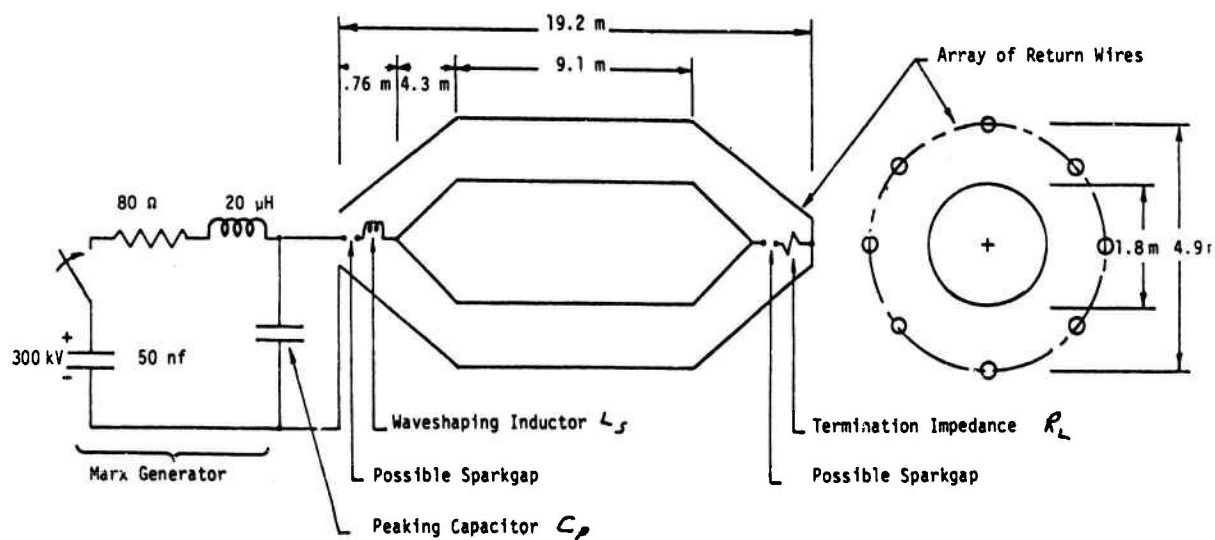


Figure 1 Basic Cylinder Configuration

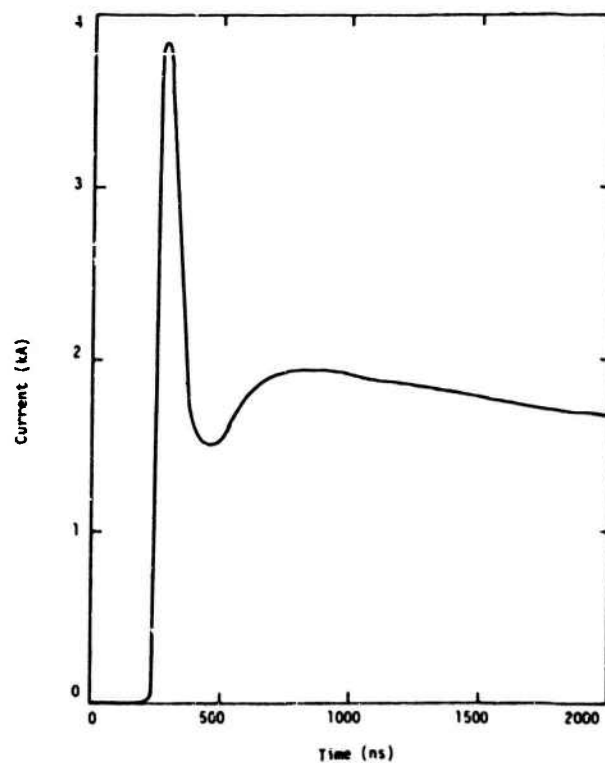


Figure 2 Injected Current for Baseline Configuration

capacitor is greatly determined by economic factors but a modest investment in a 1000 pf. capacitance can provide currents on the order of 35-40 KA with rise rates exceeding 5×10^8 A/m/s.

One item of concern is the potential need for shielding the Marx generator. This is a great cost item, and it is worthwhile to determine the extent to which a shield is needed. It was found that construction of an expensive quality overall shield is not warranted, although an inexpensive isolation flat screen would be desirable. Signal to rise ratios of 45 dB are expected.

RESPONSE OF THE RIGHT CIRCULAR CYLINDER

MODELLING APPROACH

A right circular cylinder test bed is used to provide basic configurations. The basic cylinder configuration is shown in Figure 1, which includes the Marx generator, measurement point locations, geometry, and spark gaps and terminations. This geometry is solved by treating it as a nonuniform transmission line.

The model combines the solutions for the telegrapher's equations in the test fixture itself with the solutions for the circuit which represents the Marx generator. The solution is accomplished in the time domain using finite difference techniques (1).

The geometrical inputs for the model are the per unit length capacitance and inductance which are simply related to the characteristic impedance Z_0 (2,3). The transmission line is nonuniform in that Z_0 is different on the end cones from that on the cylinder. It is not possible to taper the conic sections so that Z_0 is preserved, because of the requirement to have feed points and terminations which occupy finite amounts of space.

The cell size used was .0762 m and the time step was 100 ps.

RESULTS

A considerable number of parameters were varied to quantify the response of the cylinder in the test fixture. The parameters considered are listed in Table I.

TABLE I
PARAMETER VARIATIONS

- o Gap Locations: Front, Back, Both
- o Characteristic Impedance: No. of Wires, Distance from Cylinder, Size of Wires (6 Cases)
- o Termination Load: Open, Short, Matched, 10 Ohms
- o Series Inductance L_s : 50 nH, and for 30 ns and 300 ns Risetimes
- o Peaking Capacitance: 1 nf, e nf, 5 nf

RESPONSE OF THE BASIC configuration includes the Marx generator of Fig. 1., a peaking capacitance of 1 nf, a transmission line characteristic impedance Z_0 of 71.4 Ω , a gap at the front, a termination impedance equal to the characteristic impedance, and a series inductance which gives a risetime of 30 ns. The output spark gap fires when the voltage on the peaking capacitor reaches 300 kV.

THE INJECTED CURRENT is shown in Fig. 2.

One may observe that for this case, the response can be thought of as the sum of initial short fast risetime pulse and a long slow risetime pulse. These two pulses are relatively independent of each other and can be closely calculated by simple analytic formulas. Each pulse can be thought of as coming from an RLC circuit made up of the series combination of the peaking capacitor, waveshaping inductor, and a resistor equal to the characteristic impedance. The long pulse comes from the series RLC circuit made up of the Marx capacitance, the sum of the Marx resistance and the characteristic impedance. It is easily seen

$t = 0$

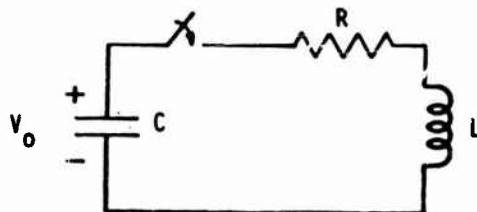


Figure 3 Simple RLC Circuit Model

that for the simple overdamped circuit of Fig. 3, if one defines

$$Z_0 = \sqrt{L/C}$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$\zeta = \frac{R}{2Z_0}$$

$$\alpha = \omega_0 \left(\zeta \pm \sqrt{\zeta^2 - 1} \right), \zeta > 1$$

then the current $I(t)$ is given by

$$I(t) = V/L (a_+ - a_-) (e^{-a_+ t} - e^{-a_- t}) \quad (2)$$

Thus each of the pulses of Fig. 2 is double exponential described by equation 2.

VARIATION OF CHARACTERISTIC IMPEDANCE

A parameter study of the of the characteristic impedance of the cylinder in the wire cage was done. Wire spacing (i.e., distance from the cylinder), the number of wires, and the wire size was varied. The results are summarized in Table 2. It can be seen that the results vary from 67 to 130 n, a span of a nominal factor of 2.

TABLE 2
CYLINDER PARAMETERS

Wire Size	Wire Space	No. of Wires	Surge Imped
.1	5	16	71.4
.1	5	8	102.0
.1	5	32	67.4
.1	10	16	109.0
.1	15	16	130.0
.6	5	16	64.8

VARIATIONS IN INJECTED CURRENT

The variation in injected current as a function of Z_0 and peaking capacitance is given in Fig. 4 and Fig. 5 respectively. It is noted that the rear gap case results in less injected current, although the exit

current would be greater in this case. Currents well over 4000 A are possible, for a drive voltage of 300 kilovolts and the importance of having as large a peaking capacitance and as small a characteristic impedance as possible is evident.

THREE DIMENSIONAL AIRCRAFT RESPONSE IN A FULL SCALE SIMULATOR

Modelling Approach - The three dimensional finite difference techniques (1) is used to model the response of a full size aircraft in a full scale simulator. The configuration is shown in Fig. 6. The large clearances are required to provide sufficient voltage stand off such that arcing of the aircraft to the outer wire grid does not occur. Voltages exceeding 6 MV are expected on the aircraft.

The aircraft is an F-16, and shape of the computer model is shown in Fig. 7. The cell size is 1 meter in the longitudinal direction, and is 1/2 meter in the other directions. The time step is 2 ns. Because approximately 5 cells are required to resolve a wavelength, the upper frequency limit of the computation is 60 MHz. The erected Marx voltage is MV. Measurement points include the injected current and E and H fields near the cockpit.

RESULTS

Results for 1000 pf peaking capacitance, a waveshaping inductance of 2 uH, and a 78 ohm termination resistor are illustrated in Fig. 8. The peak initial current of about 45 kA is unchanged with various termination resistances, but the late time responses are quite different, as expected. The aircraft resonates with the peaking capacitor initially and then with the Marx generator in the late time phases. The same basic frequency of about 5 MHz is again excited, as was the case for 200 pf peaking capacitance. Again, the late time increase in currents for the lower resistances are caused by the discharge of the Marx generator. Other oscillations at 10 MHz are evident for higher termination resistances, corresponding to the half wave resonance of the aircraft in the fixture.

Parameter studies were done for various combinations of peaking

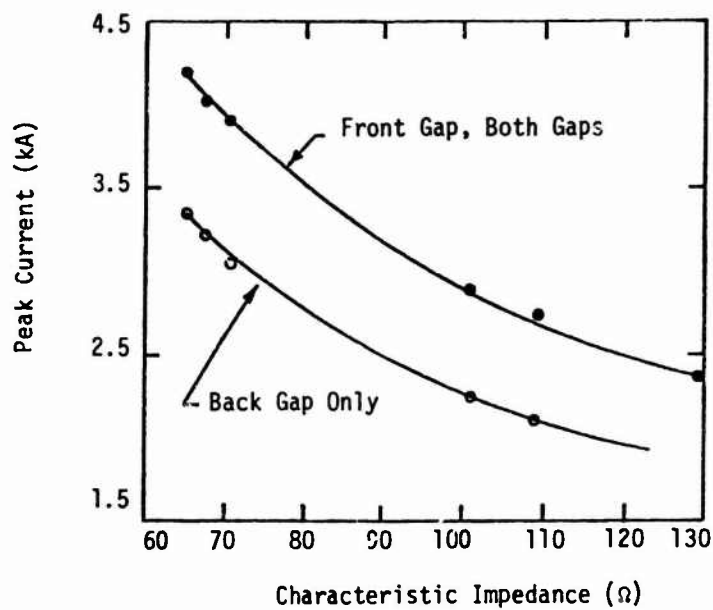


Figure 4. Variation of Peak Injected Current With Characteristic Impedance;
 $C_p = 1 \text{ nf}$; $\tau_r = 30 \text{ ns}$

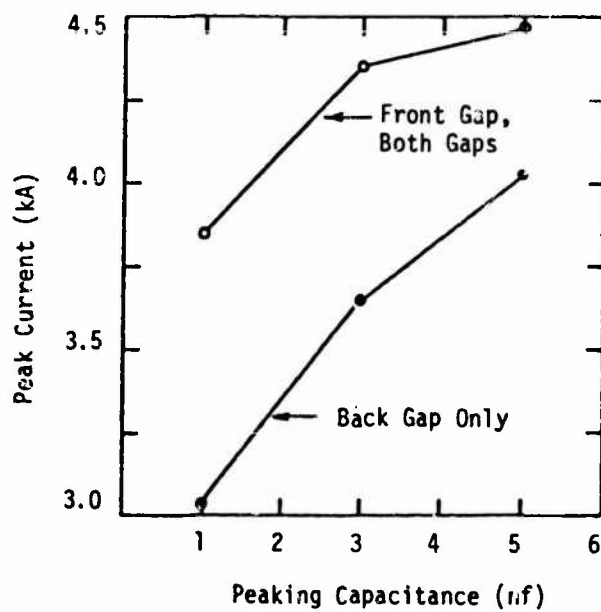


Figure 5. Variation of Peak Injected Current With Peaking Capacitance;
 $Z_0 = 71.4 \Omega$; $\tau_r = 30 \text{ ns}$

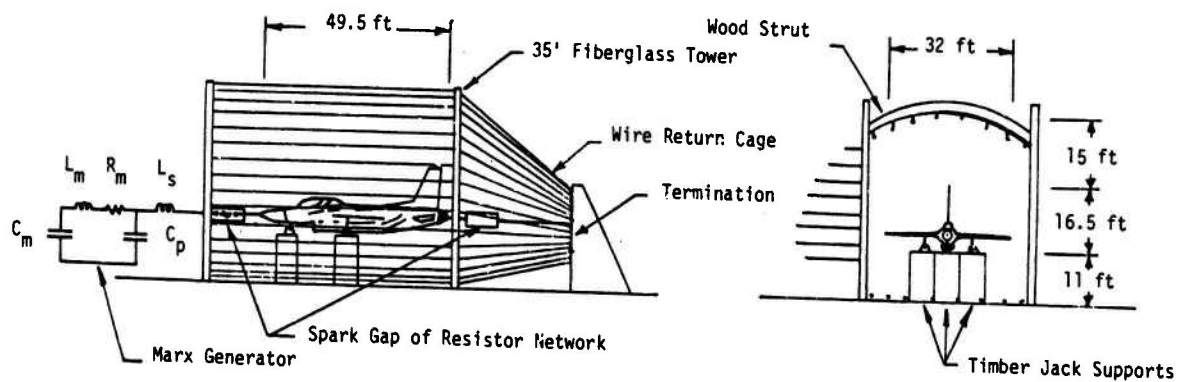


Figure 6 F-16 Aircraft in Full Scale Simulator

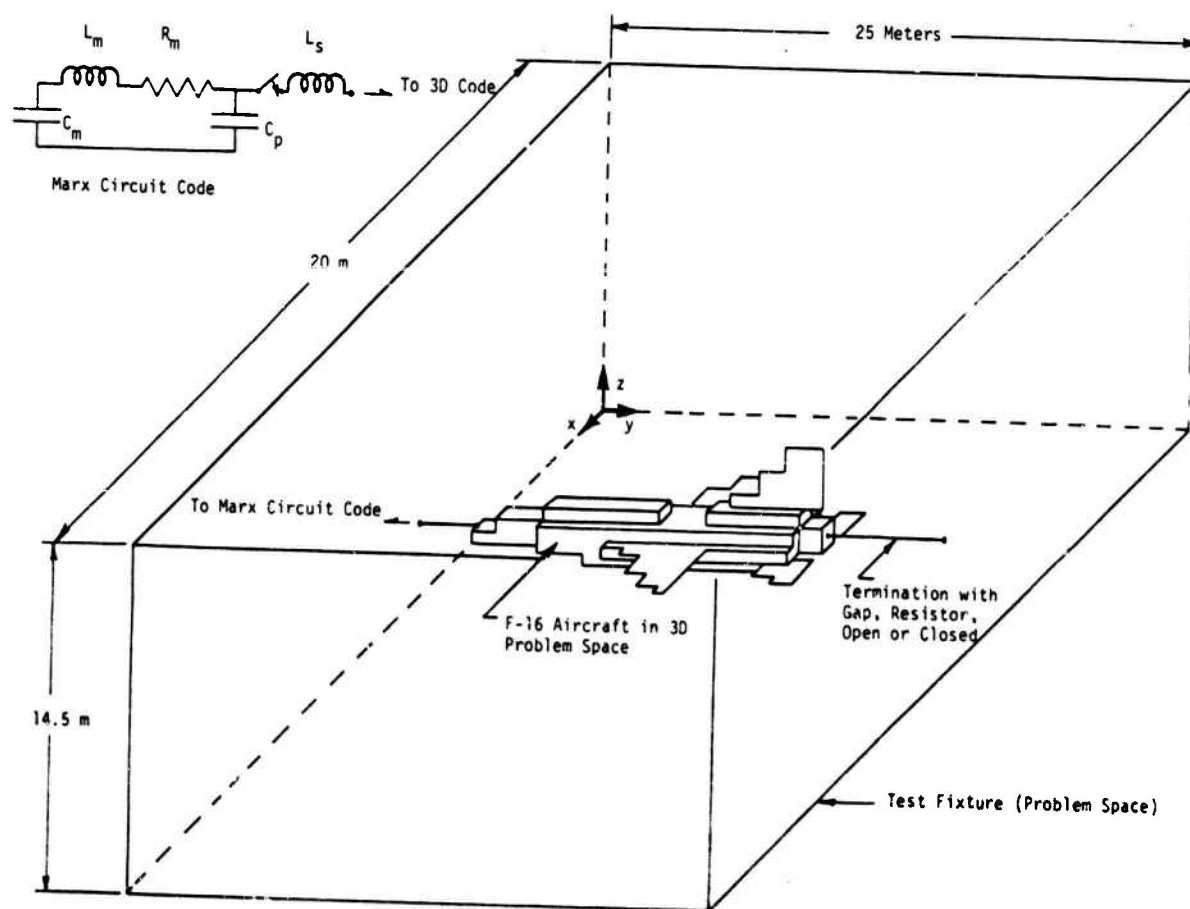


Figure 7 Three Dimensional Finite Difference Model of F-16 Aircraft in Test Fixture

TABLE 3
SUMMARY OF PARAMETER STUDY RESULTS FOR FULL SCALE SIMULATOR

C_p	L_s	t_r	I kA	I $\times 10^{11}$	H $\times 100$	H $\times 10^{10}$	E kV/m	E $\times 10^{13}$
1000	2	107	45	30	68	47	1600	13
	8	125	37	7.5	51	15	1600	4.2
	20	170	29	3	45	7	1200	2
200	2	34	27	30	44	47	1300	13
	10	100	22	6	38	12	425	3.5

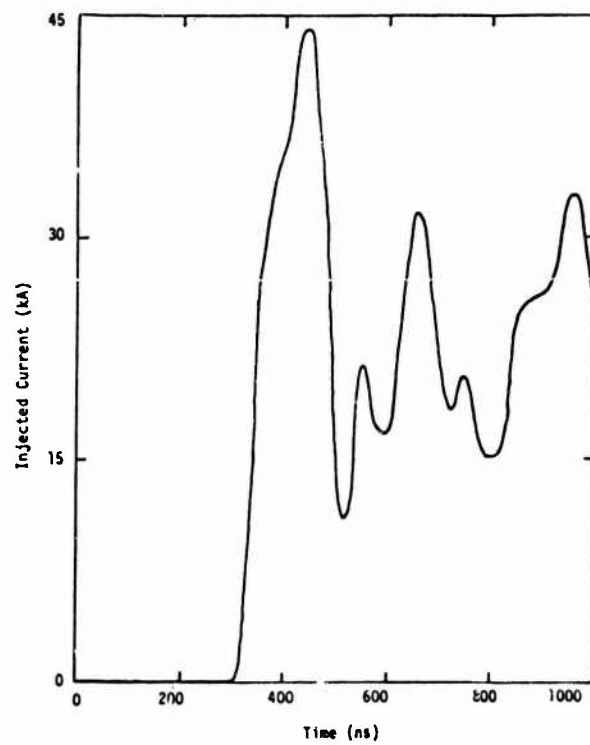


Figure 8 Injected Current for $C_p = 1000$ pf, $L_s = 2$ μ H,
and $R_L = 78$ Ω

capacitance and waveshaping inductance. The results are summarized in Table 3, which shows the rise time and injected current, magnetic field, electric field, and their derivatives. The fields are measured at the 1st point shown in Fig. 7.

Several things are evident from this data:

The level of peak injected current is greatly dependent upon the value of the peaking capacitance. This is primarily an economic decision, because large high voltage capacitors are expensive. Because L_s probably cannot be made much less than $8\mu H$, peak currents of about 35 kA are to be expected from a 1000 pf capacitance.

VALUES OF I OVER 5×10^4 A/m/sec should be obtainable with the simulator. This is in the range of values presently inferred from recent LEMP field measurements.

VALUES OF E AND H on the same order of that caused by nuclear EMP (> 10 V/m/sec and 10^4 A/m/sec respectively) are possible to achieve.

AIRCRAFT RESONANCES are excited. Their amplitudes are of course dependent upon the risetime. If the minimum achievable inductance of the peaking capacitor output circuit is on the order of $8-10\mu H$, then minimum risetimes on the order of 100 ns are probably the best one can expect.

EXPERIMENTAL STUDIES

Based on the analytical investigations, a nominal system was selected for the low level experimental tests with voltage scaling of about 10 percent and size scaling of approximately full scale. The test voltage was 200 to 300 kilovolts using a Marx generator drive. The resultant data was to be used along with the analytical data to design the full scale four megavolt system. The test arrangement is shown in Fig. 9. It consists of the Marx generator, the peaking capacitors, the feedpoint sparkgap, all housed in a weather shelter, the test object, in this case the 6-foot diameter by 30-foot long cylinder, and the downstream sparkgap or termination resistor. Plywood and 2 x 4 lumber were used in fabricating the test arrangement. The tests were carried out with the variation basically in the terminations at the far end of the array.

The result of the tests are presented in Table 4 and in the oscillograms of Fig. 10a, and b for a terminated line and a line with a far end sparkgap output. As shown in Fig. 10a, the current waveform of the experimental test arrangement showed a rise time of approximately 100 nanoseconds on the linear portion of the front of wave followed by the more slowly rising pulse from the Marx generator drive. The time duration of the impulse was approximately three microseconds. The array spacing was 5 feet from the cylinders to the wires and with 300,000 volts applied, this resulted in a radial electric field of about 150,000 volts per meter. With the 70 ohm termination, the current peak was approximately 4,000 amperes. With the far end output gap, the current oscillogram is less smooth throughout the entire duration of the wave. One of the aims in the design was to investigate the feasibility of using a non-EMP peaking capacitors in order to reduce the cost of the system and in the test arrangement, standard energy storage capacitors were used. The addition of inductance to the input of the vehicle was suggested on the basis of the analysis for cleaning up the wavefront. The solution of using additional inductance suggests that if inductance is added to the input to the vehicle, then there is no requirement for providing special low inductance peaking capacitors, and this was found to be the case, but only if a 100 nanosecond rise time is adequate. If the faster risetimes of 30 to 50 nanoseconds are required, then the input inductance must be reduced and the capacitors must be the higher cost low inductance capacitors, at the expense also of a less clean wavefront.

FULL SCALE DESIGN

The full scale test arrangement is shown in Fig. 6. The vehicle being tested is set up on wood block for insulation and the array grid is supported by fiberglass lamp posts. A simple lumber structure is used for support of the EMP peaking capacitors and these in effect act as the high voltage bushing to equalize (linearize) the voltage equally across the entrance to the transmission line array. High voltage input bushing

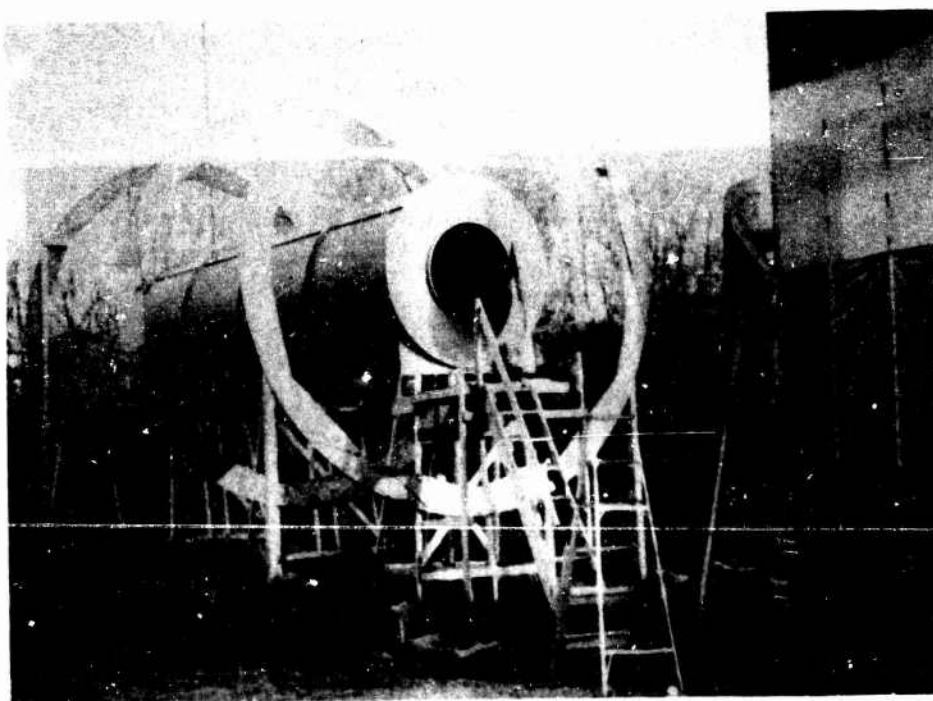


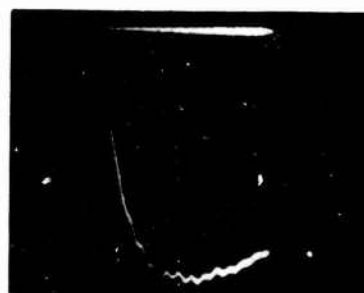
Figure 9 Photograph of Test Arrangement Showing Cylinder and Wood Support Structure Along with Wood Weather Housing For Marx Generator.

Drive Current



400 A/div

1 μ s/div



400 A/div

0.1 μ s/div

E-Field



60,000 V/div

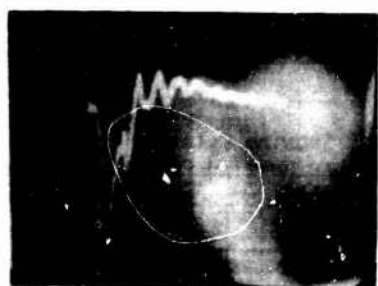
1 μ s/div



60,000 V/div

0.1 μ s/div

H-Field



100 A/div

0.2 μ s/div



100 A/div

0.1 μ s/div

Figure 10a. Oscillograms for Terminated Array.

Drive Current



800 A/div 0.4 μ s/div

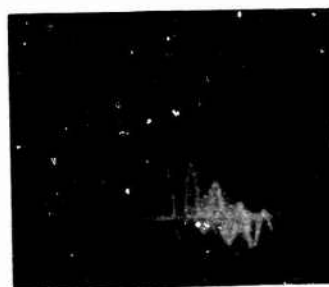


800 A/div 0.1 μ s/div

E-Field



60,000 V/div 2 μ s/div

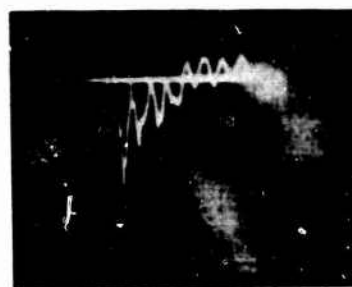


60,000 V/div 0.4 μ s/div

H-Field



100 A/div 1 μ s/div



100 A/div 0.2 μ s/div

Figure 10b. Oscilloscope traces for Array With Spark Gap Termination.

design is always a difficult problem for high voltage systems. The peaking capacitors are in effect also used to equalize the voltage across the array input to help in solving this problem.

The output firing gap and the downstream gap or termination resistor are fabricated of fiberglass gasoline storage tanks supported on a wood structure. Simple plumbing hardware is used for the sphere gaps in order to minimize the system cost.

CONCLUSIONS

The analytical and experimental studies have verified that the NEMP peaking capacitor approach can be used for lightning simulators to provide an order of magnitude improvement in current rise times over existing lightning simulators and with relatively clean wavefronts. Also, electric and magnetic field rise times and magnitudes comparable to the magnitudes measured in flight data can be obtained. Risetimes of the order of 100 nanoseconds can be obtained relatively easily, but risetimes of the order of 30 nanoseconds would be more expensive and difficult to obtain. The remaining question will be to decide what rise times should be used. Current Flight Dynamics Laboratory and NASA flight programs should help to provide data for this purpose.

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